

REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA, 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 19-10-2015	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 25-Aug-2014 - 24-Aug-2015		
4. TITLE AND SUBTITLE Final Report: 500 GHz Optical Sampler for Advancing Nonlinear Processing with Generalized Optical Pulses		5a. CONTRACT NUMBER W911NF-14-1-0591		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER 611103		
6. AUTHORS gregory kanter		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES Northwestern University Evanston Campus 1801 Maple Avenue Evanston, IL 60201 -3149		8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211		10. SPONSOR/MONITOR'S ACRONYM(S) ARO		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) 65112-PH-RIP.1		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited				
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.				
14. ABSTRACT We received a 500 GHz optical sampler for use in our optical laboratory. It has been used in support of various tasks including generating specific pump modes for tailored up-conversion processes.				
15. SUBJECT TERMS optical sampling				
16. SECURITY CLASSIFICATION OF: a. REPORT UU		17. LIMITATION OF ABSTRACT b. ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Gregory Kanter
				19b. TELEPHONE NUMBER 847-467-1801

Report Title

Final Report: 500 GHz Optical Sampler for Advancing Nonlinear Processing with Generalized Optical Pulses

ABSTRACT

We received a 500 GHz optical sampler for use in our optical laboratory. It has been used in support of various tasks including generating specific pump modes for tailored up-conversion processes.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
-------------	--------------------------

FTE Equivalent:

Total Number:

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
-------------	--------------------------

FTE Equivalent:

Total Number:

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>	National Academy Member
gregory kanter	0.00	
FTE Equivalent:	0.00	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

Names of Personnel receiving masters degrees

<u>NAME</u>
Total Number:

Names of personnel receiving PHDs

<u>NAME</u>
Total Number:

Names of other research staff

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

This equipment is used in support of experiments including tailored up-conversion experiments. We have found it to be superior to our FROG system and use it regularly. Small changes in the pulse profile are visible in near real-time.

Technology Transfer

Commercially available compact fiber-based mode locked lasers can have > 5 THz of coherent bandwidth, which is orders of magnitude beyond that obtainable with electronics. Wide bandwidth pulses have a variety of applications such as in microwave signal processing, ultra-wideband communications, and photonic analog-to-digital-conversion. Moreover, the high peak powers attainable in these short pulses make them well suited for nonlinear interactions. Nonlinear fiber optics is particularly useful due to the availability and huge installed infrastructure of low loss fiber optical cable.

Arbitrary optical waveform generation (OAWG) modifies the optical spectral amplitude and spectral phase of an optical signal in order to generate programmable optical pulse shapes. OAWGs have demonstrated sub-ps resolution control of optical pulses. Various techniques for measuring such complex optical pulses have been developed. The simplest and most robust technique is an optical sampling method which mimics the operation of more common electrical sampling oscilloscopes but allows for much larger bandwidths. While traditional samplers with optical interfaces are typically limited to ~50 GHz bandwidth, a commercial optical sampler sold by EXFO Inc. samples directly in the optical domain attaining an inherent bandwidth of 500 GHz thus allowing for temporal resolution of ~1 ps. Such a remarkable resolution is attainable without relying on complex reconstruction algorithms that are prone to artifacts nor does it rely on nonlinear spectral measurements that typically require high input optical powers. Moreover, the measurement time is not limited by the algorithm processing time or any mechanical tuning time and thus can produce accurate results much faster than other methods. This is particularly important when the measurement result is to be used to optimize a complex system with many adjustable parameters, such as an OAWG. Additionally, unlike coherent measurement techniques, the optical sampler has few requirements on the signal rate. For instance, the same instrument is capable of pulse rates up to 640 GHz. This makes the instrument useful for a huge class of experiments. The optical sampler usually does not even require a clock (trigger) input from the user, which is very convenient from the user perspective. Optical samplers can thus provide reliable high resolution temporal measurements of repetitive optical signals quickly and conveniently.

The Center for Photonic Communication and Computing (CPCC) at Northwestern University is a world leader in telecommunications-band quantum communications research, having developed the first fiber-based entangled photon source, the first ultra-fast low-loss single photon switch, and the first telecom-band linear optics C-Not gate. We have also developed classical technologies such as tunable fiber-based parametric oscillators, all optical clock recovery, and all optical pulse regeneration that are applicable to communications and metrology applications.

Recently our team has developed a series of technologies based on high speed temporal control of quantum optical signals. The methods manipulate optical pulses with temporal features typically on the order of 1-10 ps to control quantum nonlinear interactions including quantum frequency conversion (QFC). QFC has been used for many years to convert the wavelength of a quantum state to a different wavelength in order to better interface to single photon detectors or atomic interactions (quantum memories). Northwestern has extended the QFC concept to allow for heretofore impractical interactions, such as converting an arbitrary linear superposition of overlapping time-mode quantum states or efficiently frequency doubling a pulse with a bandwidth far in excess of the phase matching bandwidth. This new variant of QFC requires combining nonlinear interactions with precisely shaped optical pump pulses. It is reminiscent of optimally shaping optical pulses for coherent control of quantum mechanical processes such as ultrafast chemical reactions, a technique which has had wide implications, but in our case the pulse optimization is performed in order to tailor a nonlinear interaction to allow for previously inaccessible types of quantum measurements. When operating on

1550 nm light, the wavelength of choice for optical fibers, QFC has the additional advantage that the pump and quantum signal can both be in the 1550 nm band, which is convenient since this wavelength has copious available infrastructure. However the converted signal wavelength can be chosen for optimal detection efficiency using low cost, high efficiency Silicon single photon detectors. Over the last few years, we have built up substantial expertise for analyzing and simulating the type of multi-mode nonlinearities and quantum effects that QFC can be applied to, and we have begun a major experimental research effort to demonstrate and optimize this technology.

The CPCC has also developed all optical switches capable of controlling quantum pulses on a fast time scale with very low loss. These switches are a basic tool for manipulating quantum states and can be used for multiplexing/demultiplexing signals, generating single photon states, exceeding the classical limit on information efficiency per photon, and measuring high dimensional entanglement. The combination of high speed quantum switches and mode-selective QFC interactions can have a significant impact on quantum information science including quantum key distribution and low photon number (deep space) communications. However optimizing these types of systems generally requires precise control over optical pulses on a 1-10 ps time scale. We do have the ability to shape pulses on this time scale, for instance using a commercial “Waveshaper” from Finisar. Measuring such pulses, however, can be difficult, error prone, and time consuming.

We acquired the 500 GHz EXFO optical sampler to enhance our ability to measure short optical pulses and thus better control, simulate, and optimize the nonlinear quantum interactions of interest. Because cutting-edge experiments that manipulate quantum states usually involve combining multiple advanced technologies, it will be of great help to make the routinely required pulse measurement technique as reliable and robust as possible, thus suggesting the use of the aforementioned commercially available optical sampling equipment. The lessons learned from better quantum control can also be applied to classical experiments that utilize similar nonlinear interactions, such as optical parametric amplifiers or signal regenerators. In addition to characterizing pulses, we note that the sampler is also useful for measuring eye diagrams of very high bit rate signals, allowing us to emulate communication systems at rates which would otherwise be totally impractical to work with. This enables the university to continue to research future communication systems, and in particular the use of nonlinear signal processing to augment such systems, without requiring specialized multi-million dollar facilities.